Higgs Production through Sterile Neutrinos

based on arXiv:1512.06035

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Observation of neutrino oscillations requires \textit{at least} two of the light neutrinos to be massive.

Neutrino masses can be accounted for efficiently by right-handed or “sterile neutrinos”.

Seesaw formula: 
\[(m_\nu)_{\alpha\beta} = -\frac{1}{2} v_{EW}^2 (Y_\nu^T \cdot M^{-1} Y_\nu)_{\alpha\beta}\]
The Seesaw Mechanism

- Naïve \( (1 \, \nu_L, 1 \, \nu_R) \) version: 
  \[
  m_\nu = \frac{1}{2} \frac{v_{EW}^2 |y_\nu|^2}{M_R}
  \]

- More realistic example, the \( (2 \, \nu_L, 2 \, \nu_R) \) version:
  \[
  Y_\nu = \begin{pmatrix}
  \mathcal{O}(y_\nu) & 0 \\
  0 & \mathcal{O}(y_\nu)
  \end{pmatrix},
  \begin{pmatrix}
  M_R & 0 \\
  0 & M_R + \varepsilon
  \end{pmatrix}
  \Rightarrow
  m_{\nu_i} = \frac{v_{EW}^2 \mathcal{O}(y_\nu^2)}{M_R} (1 + \varepsilon)
  \]
  \Rightarrow \text{Knowledge of } m_{\nu_i} \text{ implies a relation between } y_\nu \text{ and } M_R.
Lowscale Seesaw

- This example uses a specific structure of the Yukawa and mass matrices that can be realised by symmetries (no fine tuning).

- A \((2 \nu_L, 2 \nu_R)\) example:

\[
Y_\nu = \begin{pmatrix}
O(y_\nu) & 0 \\
O(y_\nu) & 0
\end{pmatrix},
\begin{pmatrix}
0 & M_R \\
M_R & \varepsilon
\end{pmatrix}
\]

\[
\Rightarrow m_{\nu_i} = 0 + \varepsilon \frac{v_{EW}^2 O(y_\nu^2)}{M_R^2}
\]

- In general: no fixed relation between \(y_\nu\) and \(M_R\).

- Large \(y_\nu\) are compatible with neutrino oscillations.
The Big Picture

GUT

Leptogenesis also for larger masses
EW scale models

reactor anomaly

warm Dark Matter
Lowscale Leptogenesis

$Y_{\text{top}}$

$Y_e$

$10^{-5}$

$10^{-7}$

$10^{-9}$

$10^{-11}$

$eV$ $keV$ $MeV$ $GeV$ $TeV$ $PeV$ $EeV$ $ZeV$ $M_{\text{GUT}}$ $M_{\text{Pl}}$

Majorana Mass $M_R$

perturbativity

Neutrino Yukawa coupling $y_v$

$M^2_{\nu} = \Delta m^2_{\text{atm}}$

$M^2_{\nu} = \Delta m^2_{\text{sol}}$

Leptogenesis also for larger masses

GUT
Symmetry Protected Seesaw Scenario

- Assumption: collider phenomenology dominated by two sterile neutrinos $N_i$ with protective symmetry, such that

$$\mathcal{L}_N = -\frac{1}{2} \overline{N^1_R} M (N^2_R)^c - y_{\nu \alpha} \overline{N^1_R} \tilde{\phi}^\dagger L^\alpha + \text{H.c.}$$

- The active-sterile mixing parameter: $\theta_\alpha = \frac{y_{\nu \alpha} v_{\text{EW}}}{\sqrt{2}M}$

- The leptonic mixing matrix to leading order in $\theta_\alpha$

$$U = \begin{pmatrix}
N_{e1} & N_{e2} & N_{e3} & -\frac{i}{\sqrt{2}} \theta_e & \frac{1}{\sqrt{2}} \theta_e \\
N_{\mu1} & N_{\mu2} & N_{\mu3} & -\frac{i}{\sqrt{2}} \theta_\mu & \frac{1}{\sqrt{2}} \theta_\mu \\
N_{\tau1} & N_{\tau2} & N_{\tau3} & -\frac{i}{\sqrt{2}} \theta_\tau & \frac{1}{\sqrt{2}} \theta_\tau \\
0 & 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\
-\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & -\frac{i}{\sqrt{2}} \left(1 - \frac{\theta^2}{2}\right) & \frac{1}{\sqrt{2}} \left(1 - \frac{\theta^2}{2}\right)
\end{pmatrix}$$
Interactions between heavy neutrinos and the SM

- **Charged current (CC):**

\[ j_{\mu}^\pm = \frac{g}{2} \theta_\alpha \bar{\ell}_\alpha \gamma_\mu (\pm iN_1 + N_2) \]

- **Neutral current (NC):**

\[ j_{\mu}^0 = \frac{g}{2c_W} \left[ \theta^2 \bar{N}_2 \gamma_\mu N_2 + (\bar{\nu}_i \gamma_\mu \xi_{\alpha 1} N_1 + \bar{\nu}_i \gamma_\mu \xi_{\alpha 2} N_2 + \text{H.c}) \right] \]

- **Higgs boson Yukawa interaction:**

\[ \mathcal{L}_{\text{Yukawa}} = \sum_{i=1}^{3} \xi_{\alpha 2} \frac{\sqrt{2} M}{\nu_{\text{EW}}} \nu_i \phi^0 (\bar{N}_1 + \bar{N}_2) \]

- With the mixing parameters:

\[ \xi_{\alpha 1} = (-i) N^*_{\alpha \beta} \frac{\theta_\beta}{\sqrt{2}}, \quad \xi_{\alpha 2} = i \xi_{\alpha 1} \]
Combination of present bounds

![Graph showing bounds on $\Theta^2$ and $|y|$ vs $M$ [GeV].]

**Direct searches**
- Delphi (Z pole searches) @2$\sigma$: $|y|=\sqrt{\sum_\alpha |y_{\alpha}|^2}$, $\Theta^2=\sum_\alpha |\theta_\alpha|^2$
- LHC (Higgs decays\(^\ast\)) @1$\sigma$: $|y|=\sqrt{\sum_\alpha |y_{\alpha}|^2}$, $\Theta^2=\sum_\alpha |\theta_\alpha|^2$
- Aleph ($e^+e^- \rightarrow 4$ leptons) @1$\sigma$: $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$

**Other (global fit)**
- $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$
- $|y|=|y_{\mu}|$, $\Theta^2=|\theta_\mu|^2$
- $|y|=|y_{\tau}|$, $\Theta^2=|\theta_\tau|^2$

\(^\ast\) Currently dominated by $h \rightarrow \gamma\gamma$.

Resonant mono-Higgs from sterile neutrinos

\[ \begin{align*}
\text{Generally: } \sigma_{h\nu\nu} &= \sigma_{SM}^{h\nu\nu} + \sigma_{Non-U}^{h\nu\nu} + \sigma_{Direct}^{h\nu\nu}. \\
\sigma_{Direct}^{h\nu\nu} &\text{ from on-shell production of sterile neutrinos.} \\
&\quad \ast \text{Interference with SM-background strongly suppressed.} \\
&\quad \ast W\text{-exchange process effective at larger centre-of-mass energies, but sensitive only to } y_{\nu_e}. \\
&\quad \ast s\text{-channel production (Z boson) produces all flavours.} \\
\sigma_{Non-U}^{h\nu\nu} &\text{: indirect effect (via input parameters) from the induced non-unitarity of the PMNS matrix.}
\end{align*} \]
Using present upper bounds at 68% Bayesian confidence level.

Mono Higgs production cross section in the SM is \( \sim 54 \) fb at 250 and 350 GeV
Simulation, reconstruction and kinematic cuts

- Event simulation: WHIZARD 2.2.7
- Showering: PYTHIA 6.427
- Reconstruction: Delphes 3.2.0 (ILD card)
- Analysis: Madanalysis5
The Higgs Peak: \( |y_{\nu_e}| = 0.036 \) & \( M = 152 \text{ GeV}, \ 10 \text{ ab}^{-1} \)

Our cuts (not fully optimised):
- Pre selection: \( N_j = 2, N_\ell = 0, \ 110 < M_{jj} < 125 \text{ GeV} \)
- For the example: \( P_{jj} > 70, E_T > 15 \text{ GeV} \)

Event counts: (starting with pre selection)
- BKG: \( 548.584 \rightarrow 18.627 \) \( \Rightarrow \frac{S}{\sqrt{S+B}} \sim 30! \)
- \( \sigma_{h\nu\nu} \) Direct: \( 15.335 \rightarrow 4.846 \)
Contamination of SM parameters

\[ \frac{\sigma_{\text{inv}}}{\sigma_{\text{SM}}} - 1 \]

\[ \sum_{h} \text{NN} / \sum_{h} \text{NN} \]

\[ \text{SM} / \text{M}_{\text{Nu}} \]

\[ E_{cm} = 240 \text{ GeV} \]
\[ E_{cm} = 350 \text{ GeV} \]
\[ (\sigma_{\text{bbv}}(240 \text{ GeV}) \times 10 \text{ab}^{-1})^{-1/2} \]
\[ (\sigma_{\text{bbv}}(350 \text{ GeV}) \times 3.5 \text{ab}^{-1})^{-1/2} \]

Standard cuts for Higgs events at lepton colliders:

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>240 GeV</th>
<th>350 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Missing Mass [GeV]</td>
<td>$80 \leq M_{\text{miss}} \leq 140$</td>
<td>$50 \leq M_{\text{miss}} \leq 240$</td>
</tr>
<tr>
<td>Transverse P [GeV]</td>
<td>$20 \leq P_T \leq 70$</td>
<td>$10 \leq P_T \leq 140$</td>
</tr>
<tr>
<td>Longitudinal P [GeV]</td>
<td>$</td>
<td>P_L</td>
</tr>
<tr>
<td>Maximum P [GeV]</td>
<td>$</td>
<td>P</td>
</tr>
<tr>
<td>Di-jet Mass [GeV]</td>
<td>$100 \leq M_{jj} \leq 130$</td>
<td>$100 \leq M_{jj} \leq 130$</td>
</tr>
<tr>
<td>Angle (jets) [Rad]</td>
<td>$\alpha &gt; 1.38$</td>
<td>$\alpha &gt; 1.38$</td>
</tr>
</tbody>
</table>

Sensitivity of the mono-Higgs channel to neutrino mixing

Considered:
10 \text{ ab}^{-1} \text{ for } 240 \text{ GeV}, 3.5 \text{ ab}^{-1} \text{ for } 350 \text{ GeV}, 1 \text{ ab}^{-1} \text{ for } 500 \text{ GeV}

Summary and conclusions

▶ Sterile neutrinos are well motivated extensions of the SM.
▶ Symmetry protected scenarios allow for large Yukawa couplings and masses in the interesting range.
▶ **Higher center-of-mass energies lead to increased mono-Higgs production cross sections from sterile neutrinos.**
▶ $\sqrt{s} = 350$ GeV is even more sensitive than 240 GeV.
▶ A contamination of the Higgs sample can lead to a $3\sigma$ deviation of the SM parameters.
▶ Sensitivity to $|y_{\nu e}|$ down to $6 \times 10^{-3}$ is possible.
  ⭐ **Important for understanding the data.**
  ⭐ **Complementarity** to other searches for sterile Neutrinos.
▶ For other search channels, see: Antusch, OF; arXiv:1502.05915 (2015)
Thank you for your attention.
Backup I: Prospects of Sensitivity at the CEPC

Direct searches
- Z pole search @2\sigma: \(|y| = \sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}, \Theta^2 = \sum_\alpha |\theta_\alpha|^2\)
- Higgs → WW @1\sigma: \(|y| = \sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}, \Theta^2 = \sum_\alpha |\theta_\alpha|^2\)
- e^+e^− → h + ME(T) @1\sigma: \(|y| = |y_{\nu_e}|, \Theta^2 = |\theta_e|^2\)
- e^+e^− → lνl^∗ @1\sigma: \(|y| = |y_{\nu_e}|, \Theta^2 = |\theta_e|^2\)

Other
- Precision constraints: \(|y| = \sqrt{|y_{\nu_e}|^2 + |y_{\nu_\mu}|^2}, \Theta^2 = |\theta_e|^2 + |\theta_\mu|^2\)
- Precision constraints: \(|y| = |y_{\nu_e}|, \Theta^2 = |\theta_e|^2\)
- "Unprotected" type–I seesaw


* Preliminary estimate using statistical uncertainty only.
From “indirect” tests and Delphi.

$O(1)$ branching ratio possible.

⇒ Possible effect on Higgs decay rates into Standard Model particles.
Backup III: Cross sections for SM background

<table>
<thead>
<tr>
<th>Final state</th>
<th>$\sigma^{\text{SM}}@240$ GeV</th>
<th>$\sigma^{\text{SM}}@350$ GeV</th>
<th>$\sigma^{\text{SM}}@500$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}\nu\nu$</td>
<td>146.492</td>
<td>134.614</td>
<td>183.594</td>
</tr>
<tr>
<td>$c\bar{c}\nu\nu$</td>
<td>88.0172</td>
<td>73.7956</td>
<td>82.7041</td>
</tr>
<tr>
<td>$jj\nu\nu$</td>
<td>528.8</td>
<td>463.1</td>
<td>500.3</td>
</tr>
<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>81.2629</td>
<td>47.6152</td>
<td>25.5571</td>
</tr>
<tr>
<td>$b\bar{b}c\bar{c}$</td>
<td>146.566</td>
<td>87.6518</td>
<td>51.6446</td>
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<tr>
<td>$bbjj$</td>
<td>6820.6</td>
<td>4259.5</td>
<td>2537.8</td>
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<tr>
<td>$b\bar{b}e^+e^-$</td>
<td>2080.87</td>
<td>2500.82</td>
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<td>$b\bar{b}\tau^+\tau^-$</td>
<td>34.1905</td>
<td>19.7975</td>
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<tr>
<td>$c\bar{c}\tau^+\tau^-$</td>
<td>25.2553</td>
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<tr>
<td>$jj\tau^+\tau^-$</td>
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<tr>
<td>$\tau^+\tau^-\nu\nu$</td>
<td>235.89</td>
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<tr>
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<td>0.012</td>
<td>63.3</td>
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<tr>
<td>$tt$</td>
<td>—</td>
<td>322.</td>
<td>574.</td>
</tr>
</tbody>
</table>

All cross sections in fb.
Backup IVa: High Energy Physics Time Scales

- **LEP**
  - Design: 1980
  - Proto: 1990
  - Construction: 2000
  - Physics: 2010

- **LHC**
  - Design: 2020
  - Proto: 2030
  - Construction: 2040
  - Physics: 2050

- **HL-LHC**
  - Design: 1980
  - Proto: 1990
  - Construction: 2000
  - Physics: 2010

- **Future collider**
  - Design: 2020
  - Proto: 2030
  - Construction: 2040
  - Physics: 2050

- **Today**